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TIME DOMAIN ANALYSIS OF OCEAN CLUTTER IN HIGH FREQUENCY RADAR

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ABSTRACT

High frequency (HF) radar has the unique potential for over-the-horizon detection of ocean surface targets. However, ocean waves are also strong reflectors for HF radar and this high clutter level has limited its application for target detection. Results from the time domain analysis of ocean clutter show that it can be modelled as two angle modulated signals; the two 'carrier' frequencies correspond to the theoretically predicted 'Bragg' Doppler frequencies. This characterization of ocean clutter makes it possible to adapt existing time domain techniques to estimate and, if desired, suppress the clutter signal. Enhanced target detection will be demonstrated.

I. INTRODUCTION

High frequency (HF) electromagnetic waves, propagating along the ocean surface in the ground-wave mode, are strongly reflected by certain ocean waves. Crombie[1] first observed this effect and attributed the dominant component of returned energy to back-scattering from ocean waves having a wavelength half that of the radar wavelength. Two sets of such ocean waves, moving radially to and away from the transmission site respectively, behave as diffraction gratings and cause constructive interference of the scattering returns. These scattering returns exhibit two distinct Doppler frequencies corresponding to the characteristic velocity of propagation of the two sets of ocean waves. Fig. 1 shows these two 'Bragg' scattering frequencies for an HF radar operating at 25.4 MHz; at this frequency the 'Bragg' scattering is due to ocean gravity waves of about 5.9 m wavelength. The characteristic propagation speed of about 10.9 km/hr of these 'Bragg' waves translates to a Doppler frequency of 0.51 Hz.

In addition to the dominant 'Bragg' scattering returns, a smaller and more complicated feature of the HF radar Doppler spectrum is referred to as the 'second order' scattering. Using different approaches, Barrick[2] and Walsh[3] have derived similar analytical expressions for the ocean clutter radar cross section in the HF band. This cross section, evaluated as a function of the radar Doppler frequency, contains the first and second order scattering components and is related to the directional ocean wave-height spectrum.

The impact of ocean clutter on target detection may be appreciated by the fact that the first order clutter cross section, from 'Bragg' ocean waves travelling with the wind, is typically much stronger than the cross section of a ship target. A ship target thus cannot be detected if it is moving with a velocity close to that of the 'Bragg' waves, so that Doppler frequency discrimination is not possible. Depending on the size of the ship and the sea state, even the second order clutter cross section can mask the target. These concerns were addressed by Maresca and Barnum[4], who investigated the feasibility of detecting ships with HF radar. Their results stated, in essence, that the ocean clutter would limit target detection in significant portions of the Doppler spectrum. The resulting extent of target blind speeds would thus make such a radar device impractical.

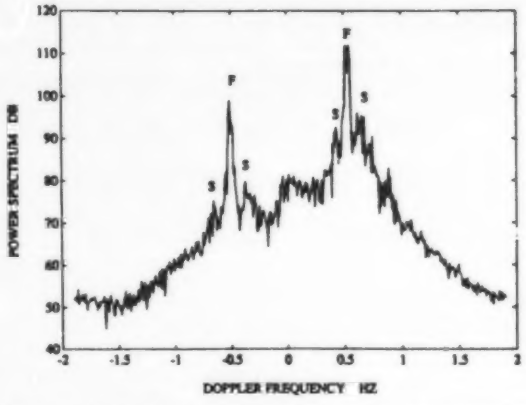

Fig. 1 Typical HF radar power spectrum showing the characteristics first- (F) and second-order (S) scattering components.

If HF radar is to be used for low Doppler target detection, then some characteristic differences, other than Doppler frequency, between the clutter and target signals must be established. These characteristic differences could then be utilized to effect a separation of target signals from the ocean clutter signals; this would decrease or even eliminate the blind speed ranges. In an earlier publication[5], we reported that the dominant 'Bragg' ocean clutter signal exhibits some time-varying characteristics. Section II describes furthur detailed investigation of the time-varying behaviour of the ocean clutter and shows that the clutter can be modelled by two narrowband signals, with time-varying frequencies, centred around the two 'Bragg' frequencies. The time varying frequency characteristic of the two narrowband

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clutter signals can be interpreted as being due to two independent angle modulations. It is demonstrated that the spectrum of such an angle modulated signal agrees closely with the spectrum of HF radar data, and accounts for the characteristics corresponding to both the well known first- and second-order scattering peaks.

The interpretation of ocean clutter as two independent angle modulated signals allows the use of low order adaptive filters to model the clutter signals. Section III describes how, in the presence of a target signal, simple time-domain processing may be used to selectively suppress the dominant clutter signals.

II. TIME-VARYING CHARACTERISTICS OF HF OCEAN CLUTTER

This section describes the results of our study of the time-varying frequency characteristics of HF radar ocean clutter signals. The need to estimate signal parameters over short data segments prompted us to apply parametric and adaptive methods to these signals. Specifically, simple estimation algorithms, based on the well known technique of linear prediction, were used to establish the following characteristics of ocean clutter signals:

a) In a short time frame, the clutter signal consists essentially of two narrow-band Doppler signals only, corresponding to the two 'Bragg' scattering frequencies.

b) The frequencies of the two narrowband Doppler signals vary with time; their average values agree with the theoretically predicted 'Bragg' Doppler frequencies.

c) A low order prediction filter, with time-varying coefficients, adequately models both the first and second order Doppler spectra.

A. Linear Prediction Model

It is well known that, at high signal-to-noise (SNR) ratios, linear prediction (LP) or autoregression (AR) based methods can be effectively used to estimate the parameters of sinusoidal signals. The basis of the AR parametric model of a signal is that its value $\hat{x}(k)$, at any time instant, can be predicted as a weighted sum of L previous values[4]:

$$\hat{x}(k) = -\sum_{i=1}^{L} x(k-i) \cdot a_i \qquad (1)$$

In equation (1), L is the order of the prediction filter. A prediction error filter (PEF) performs the operation of subtracting the predicted signal value from the actual signal value. It is important to note that, if the signal fits this parametric model, then the output of the PEF is white.

The prediction error filter (PEF) is an all zero filter and it can be shown that, for a signal containing M sinusoids, the transfer function of the PEF has M zeros on the unit circle at the angular locations corresponding to the angular frequencies of the M sinusoids in the signal[7]. It can also be shown that if the PEF has L zeros, where L > M, then the L-M extraneous zeros are uniformly distributed in angle around the inside of the unit circle. These properties of the PEF can be used to test the hypothesis that the ocean clutter signal contains only two narrow-band sinusoids with time-varying frequencies near the Bragg frequency. During a short time frame, the number of zeros of the PEF on the unit circle determine the number of sinusoids in the signal and their angular positions determine the frequencies of the sinusoids.

To track the proposed time-varying behaviour of the ocean clutter signal, the coefficients of the prediction error filter must be estimated using very short data segments; alternately an adaptive scheme may be implemented to continuously update their values. It can be easily shown that the transfer function of the PEF can be directly written as:

$$H(z) = 1 + \sum_{i=1}^{L} a_i z^{-i} \qquad (2)$$

As mentioned above, the zeros of H(z) lying at or very close to the unit circle determine the number of sinusoids present in the signal.

The technique of linear prediction can be easily implemented to operate in an adaptive mode. Fig. 2 shows the block diagram of an adaptive prediction error filter. The adaptive filter attempts to minimize the error between the input signal and the filter response from a single sample delayed version of the input; the filter adapts towards a prediction filter. This scheme was implemented using the subroutine SPNLMS[8], which is based on the well known LMS algorithm[9]. The filter coefficients $a_i(k)$ are updated, for each input sample, according to the following:

$$A(k+1) = A(k) + \frac{2 \cdot \mu \cdot e(k) \cdot X(k)}{(L+1) \cdot [\sigma(k)]^2} \qquad (3)$$

$$[\sigma(k)]^2 = \alpha \cdot [x(k)]^2 + (1-\alpha) \cdot [\sigma(k-1)]^2$$

where $A(k) = [a(k)\ a(k)\ \ldots\ a(k)]$

$X(k) = [x(k)\ x(k-1)\ \ldots\ x(k-L)]^T$

$0 < \mu < 1$

$0 < \alpha \ll 1$

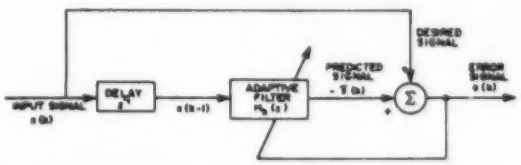

Fig. 2 Block diagram of an adaptive filter operating in the prediction mode

The adaptation performance of the algorithm is controlled by the two parameters μ and α. The first parameter μ is called the convergence parameter which must be matched to the signal statistics. If μ is too large, the filter coefficients change rapidly to compensate for instantaneous errors but convergence to the true

value may be very slow. Conversely, if μ is too small the system may not react rapidly enough to cope with changing signal statistics. The parameter α is referred to as a forgetting factor and enables operation in non-stationary environments. As seen in equation (3), updating the variable α is done in such a manner that the past values of x(k) are weighted exponentially and their effect becomes negligible after a time period corresponding to approximately $1/\alpha$ samples.

B. Experimental System

The experiments were performed using a CODAR (Coastal Ocean Dynamics Applications Radar) system. This is a 25.4 MHz radar system originally designed to measure ocean surface currents; it has been modified here to enable operation with a narrow-beam receive antenna. The wide-beam transmit antenna consisted of a three element Yagi array and the receive antenna was a twelve element quarter wave monopole array with a 9.45 metre spacing. The experiments were located at various beaches in Newfoundland with the antennas just above the high water mark.

C. Frequencies in Ocean Clutter Signal

The first objective was the determination of the number of sinusoids contained in the ocean clutter signal. If the frequencies of these sinusoids vary with time then the prediction coefficients for this signal would also exhibit a time variation. Thus, using the adaptive PEF described above, the roots of the PEF transfer function were evaluated at every iteration to determine the locations of the zeros. Using HF radar data from an ocean cell, at a range of 6 km, Fig. 3 is a cluster plot of 425 sets of PEF transfer function zeros computed at time intervals of 0.262144 s. The length of the prediction filter used was three and it is seen that only two zeros are clustered near the unit circle. The angular location of the cluster centres correspond to the two theoretically predicted Bragg frequencies. The location of the third cluster, well within the unit circle, denies the existence of a third sinusoid'.

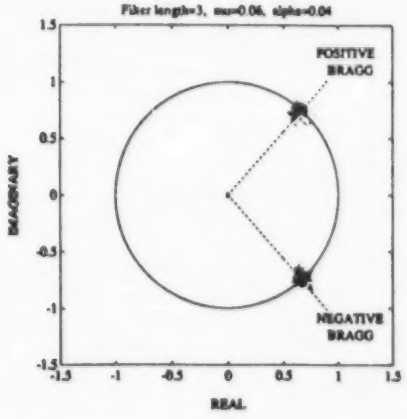

Fig. 3 Cluster plot of adaptive PEF transfer function zeros. Input to filter was HF radar data with ocean clutter signal only.

As a further test, Fig. 4 was obtained using a PEF of length 9. Again, it is seen that only two roots cluster on the unit circle confirming that the signal contains two sinusoids only. None of the remaining seven roots approach the unit circle.

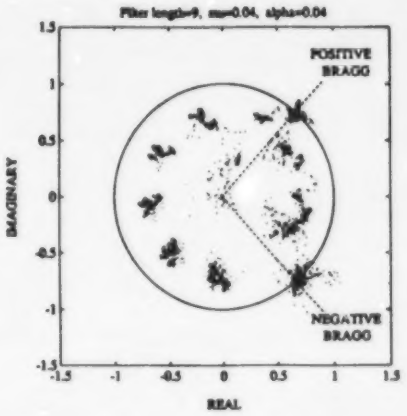

Fig. 4 Root cluster plot, similar to Fig. 3, corresponding to a higher order adaptive PEF. Only two roots cluster on unit circle indicating a signal with two sinusoids.

Both Figs. 3 and 4 show a significant spread, in angular position, of the two roots clustered on the unit circle. The spread in angular position is directly related to the frequency variations of the corresponding sinusoids. Similar cluster plots have been obtained using a number of different HF radar data sets. These tests led to the conclusion that the ocean clutter signal contains two narrowband sinusoids, with time-varying frequencies, centred around the theoretically predicted Bragg frequencies.

Referring to Fig. 2, the signal $\hat{x}(k)$ is effectively a modelled version of the input signal based on a time-varying prediction filter of order L. Fig. 5 demonstrates the close correspondence between $\hat{x}(k)$ and x(k) using an adaptive prediction filter of length 3. The performance of this modelling can be judged more easily by comparing the spectra of the input and modelled signals as shown in Fig. 6. The spectrum of the modelled signal in Fig. 6b clearly reproduces the main characteristics of the input spectrum; the well known first and second order Doppler clutter components have been accurately modelled. It must be noted that no significant effort has been made yet to optimize the parameters of the adaption algorithm which may improve the modelling performance.

D. Time-varying Behaviour of 'Bragg' Frequencies

There is a direct correspondence between the angular position of the zeros of the PEF transfer function and the frequency of the sinusoid contained in the signal. Thus, by analyzing the zero locations at each iteration, the time variations of the sinusoids in the clutter signal could be established. Using the same data as in the previous sub-section, Fig. 7 shows the estimated time variations of the frequencies of the ocean clutter signal.

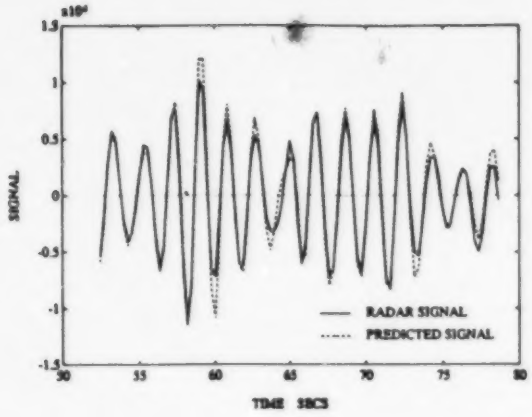

Fig. 5 Comparison of true and predicted values for an adaptive prediction filter of length 3, operating on ocean clutter signal.

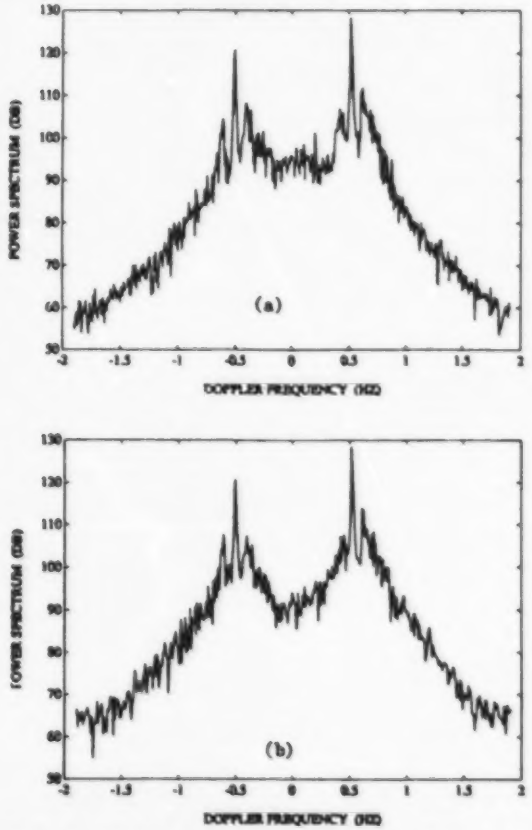

Fig. 6 Comparison of the spectra of the signals in Fig. 5. a) Spectrum of ocean clutter signal. b) Spectrum of modelled ocean clutter at output of prediction filter.

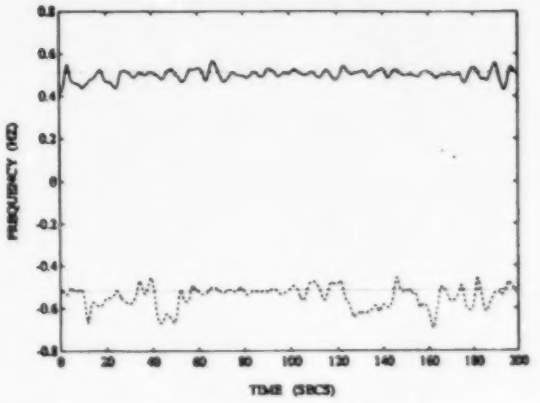

Fig. 7 Time-varying behaviour of the two dominant narrowband frequency components in HF radar ocean clutter.

We believe that these observed frequency variations of the ocean clutter signal may contain answers to a number of questions regarding the interaction of HF radar with ocean waves and may provide insight into the fundamental behaviour of ocean waves. The first obvious interpretation of Fig. 7 is simply that the 5.9 metre ocean waves, corresponding to the Bragg frequency, are not moving with a constant velocity. Rather, possibly due to interaction with other ocean waves, their velocity is constantly changing about an average velocity. It can be easily shown that this velocity variation would cause an angle modulation of the radar Doppler return, causing the observed frequency variations. Based on this interpretation, a composite description of the ocean surface obtained using HF radars operating at different wavelengths could enhance our understanding of the ocean waves.

III. CLUTTER SUPPRESSION FOR TARGET DETECTION

The results of the previous section clearly show that the main characteristics of the ocean clutter signal can be easily modelled using a low order adaptive predictive filter. In this section a simple technique is presented to increase the signal to clutter ratio for HF returns from a target.

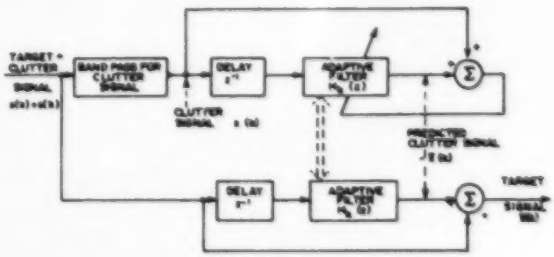

Fig. 8 Signal-to-clutter ratio enhancement using an adaptive prediction filter.

Using the HF radar system described earlier, an ice detection experiment was performed at Lumsden Beach, Bonavista Bay in Spring 1989. The data to be analyzed contained an iceberg target with a water line area of about 155 m². The range to the iceberg was 8.4 km and, as the iceberg was moving across the radar boresight, had a very low radial Doppler velocity component. Assuming two sinusoidal components for the ocean clutter, the radar signal now contains an additional third signal component. As a first attempt at clutter suppression, the scheme illustrated in Fig. 8 was used. We want to design an adaptive prediction filter for the clutter components of the signal only. This may be achieved by first applying a bandpass filter to the input signal to isolate the clutter components. In this example an extremely simple two pole bandpass filter was used; at the Bragg frequencies the maximum gain of the filter was 16.6. This bandpass signal was input to an adaptive prediction filter. Due to the bandpass suppression of the target signal, it did not contribute appreciably to the prediction filter coefficients. In other words, the prediction filter was designed to model the clutter signal only. When the same prediction filter was applied to the original radar data, it effectively cancelled out the clutter components and did not affect the target signal. The resulting enhancement of the signal to clutter ratio is clearly shown in the next figure. Fig. 9a shows the spectrum of the unprocessed radar signal, containing the two Bragg components as well as a low Doppler iceberg signal. The output spectrum in Fig. 9b, after time-domain processing with an adaptive prediction filter of length 3, demonstrates that the clutter components have been suppressed by about 40 dB and the iceberg signal is effectively unchanged.

It is expected that extensions of this simple technique presented here could result in robust and reliable methods for low Doppler target detection using HF radar. For example, the statistics of the clutter frequency variations could be estimated using a number of neighbouring range cells. This could allow the influence of target signal in updating the adaptive filter coefficients to be minimized. This would be specially critical in situations where the Doppler frequency of the target signal falls close to the dominant Bragg frequencies. Work on this aspect is progressing and will be reported soon.

IV. CONCLUSIONS

A few fundamental time domain characteristics of HF radar ocean clutter signals have been established. Specifically, it is shown that the ocean clutter may be adequately modelled with two narrowband Bragg signals with time-varying frequencies. Low order adaptive prediction filters can thus be used to suppress the ocean clutter. Simple adaptive filters can also be designed to improve the signal to clutter ratio for low Doppler target signals.

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The contribution of Mr. Ken Klein who performed the ice detection experiment at Lumsden Beach is gratefully acknowledged.

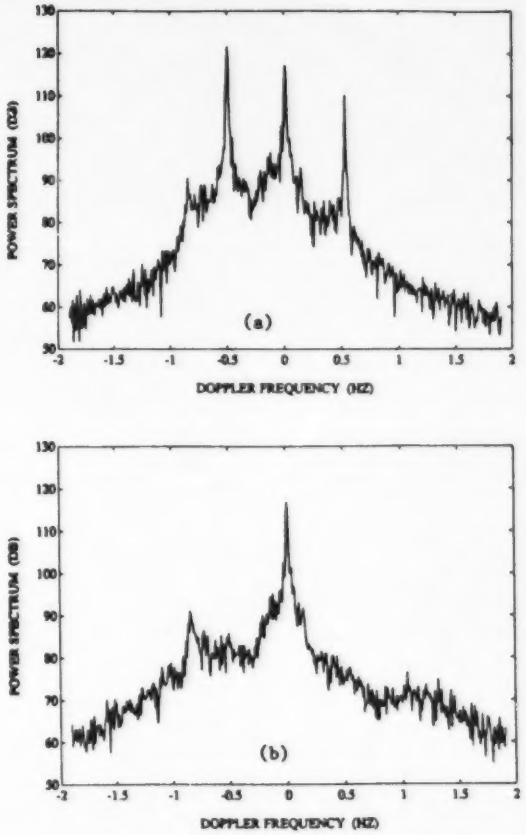

Fig. 9 Comparison of the spectra, before and after adaptive processing, for the iceberg detection experiment. a) Spectrum containing iceberg and clutter signals. b) Enhanced spectrum after clutter suppression.

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